Soft Robotic Tongue Mimicking English Pronunciation Movements 2nd Report: Fabrication and Experimental Evaluation

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Abstract: A novel soft robotic tongue mimicking the movements of English pronunciation was proposed, aiming at the learning support for English pronunciation. A soft robotic tongue's system design and actuator arrangements have been proposed, and the Finite Element Methods (FEM) simulation for each deformation has been conducted. In this paper, we discussed two milestones: fabrication and experimental evaluation. The fabrication, molding, and casting method was applied to the model, and it was manufactured five times bigger than the original size of a human tongue. A silicone rubber Ecoflex 00-30 was utilized and poured into the mold that was preliminary printed with a 3D printer. Moreover, an experiment was conducted to confirm and evaluate the deformation patterns of English pronunciation movements. A ruler was used to measure the parameters in each deformation, such as bend and flap angle, and bulge height. It presented that bend and bulge deformations between the fabricated soft robotic tongue and simulated FEM results were likely the same; however, the flap deformation slightly differed in the experimental evaluation.

1 INTRODUCTION

Before we dive into current research, we were experimenting with the practical use of humanoid robots to improve Japanese' English pronunciation and prosody (Krisdityawan et al., 2022). When the experiment was done, we received a critical comment from the participants: they did not know how to move their tongue in the particular sound of English pronunciation. Specifically, R (/r/), L (/l/), Th- (θ and ð), F (/f/), and V (/v/) sound. The humanoid robot we used does not have a function to move the mouth and tongue. Therefore, we aim to develop a robotic tongue to visualize the movements during pronouncing English words, aiming at learning support. We considered the universality of the robotic tongue that we design can be used for non-native English speakers; however, in this paper, our target is to support Japanese people learning English pronunciation by showing the visual of tongue movements.

The tongue movements during pronouncing English words are aggressive and have a high flexibility rate. To design a robotic tongue that can mimic English pronunciation movements, it needs to determine what kind of concept we want to apply and assign the tongue materials that will be used. Compared to other works of tongue robotics, they mainly develop a structure consisting of rigid materials or use a skeletal structure (Endo et al., 2020; Hofe et al., 2008; Marconati et al., 2020; Zheng et al., 2018; Shijo et al., 2019), and the movements were stiffed. To increase the elasticity and flexibility, some papers (Lavoisier et al., 2022; Darmont & Radhakrishnan, 2021) developed a tongue robot using the fundamentals of soft robotics. These works used Ecoflex 00-30 silicone rubber and polydimethylsiloxane (PDMS) (Lavoisier et al.,

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2022) as their materials and actuating their robot with air pressure or "PneuNets" (pneumatic network). PneuNets is a series of chambers embedded in an elastic material connected to an inelastic layer, and it starts to inflate when air is pressurized. Using PneuNets, our robot can increase the flexibility in movements and speed close to humans when pronouncing English words.

Designing our soft robotic tongue should fulfill the conditions of basic tongue movements in English pronunciation. We analyzed the basic movements using software called "Pronunciation Coach 3D" (icSpeech, n.d.). Basic tongue movements during pronouncing English sounds are distinguished into three movements: bend, bulge, and flap shown in Figure 1. Bend is when the tongue tip starts to lift at a certain angle and can be found at L (/l/) sound. Bulge is when the middle part of the tongue begins to bulge or lift at a certain height, which can be found at R (/r/) sound. The flap is a movement when both the left and right parts of the tongue lift symmetrically and circularly to the middle part, similar to the letter U or V, found in Th- (θ and ð) sound. All parameters, such as angle, length, and height summarized in Table 1. A parameter L_{tip} and θ_{flap}were revised from 0.12 to 0.21 and 60 degrees to 38 degrees due to typing error during data acquisition. The parameter was normalized into 1 to make it easier for us to fabricate the actual tongue robot with different scales or sizes. The details of the design description will be discussed in the next section.

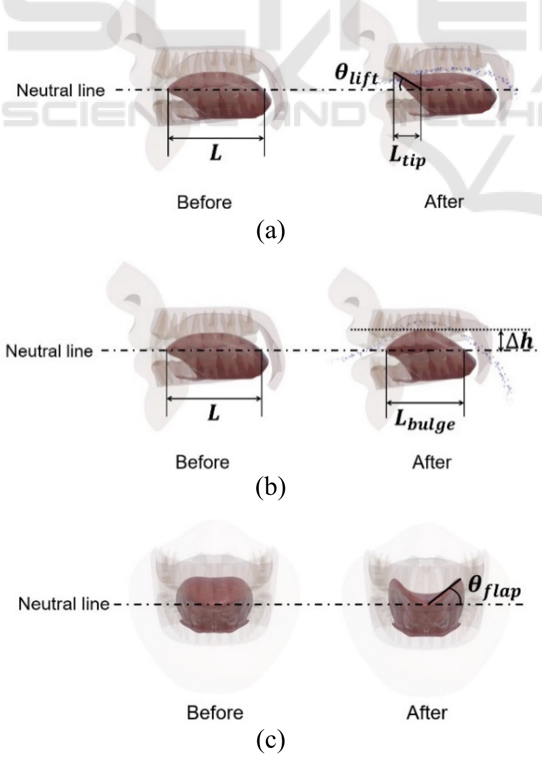

Figure 1: Three basic tongue movements during English pronunciation: (a) bend movement. (b) bulge movement. (c) flap movement.

Table 1: Ratio designed parameters of the tongue.

Parameter notation	Ratio
L	1.00
L_{tip}	0.21
θ_{lift} [deg]	10
θ_{flap} [deg]	38
Δh	0.22
L_{bulge}	0.95

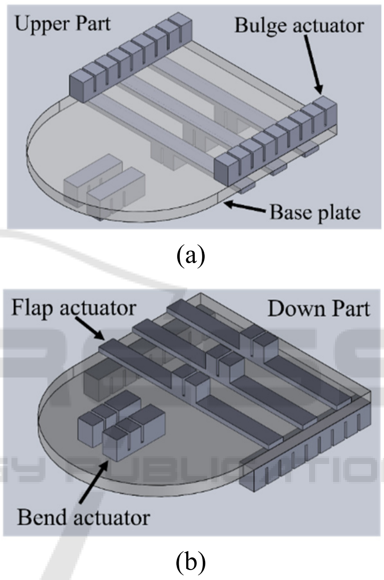

Figure 2: Overall soft robotic tongue (a) upper part design. (b) down part design.

2 PREVIOUS RESEARCH

Ahead of our current progress, we would like to review our previous research (Krisdityawan et al., 2023) that will discuss the design of our novel soft robotic tongue and verify the proposed system using FEM (Finite Element Methods) simulation.

2.1 Design Description

The soft robotic tongue design that we proposed is shown in Figure 2. It comprises a base plate and three soft actuators attached to the base plate that can be satisfied from three basic movements during English pronunciation.

2.2 FEM Simulation

Based on our proposed design, we conducted simulations using Ansys Mechanical to verify the deformation. The simulation flow chart is depicted in Figure 3. It is divided into seven milestones, and the details explanation is described in Table 2.

Table 2: Seven milestones and details of the simulation.

No.	Milestone	Description
1	Model Design	3D model CAD data made with SolidWorks and imported to Ansys
2	Assign Material	Assign the material which is hyperelastic material (Ecoflex 00-30)
3	Insert Constrain	Setting up Young's modulus, Poisson's ratio, and Yeoh 2nd orders
4	Mesh	Defining 3D shape with polygonal representation.
5	Analysis Setting	Setting up the analysis including pressure, earth gravity, fixed point, frictionless between walls, and activate large deflection
6	Calculation	Calculate the simulation based on the settings and conditions
7	Result	Showing the result of the FEM simulation

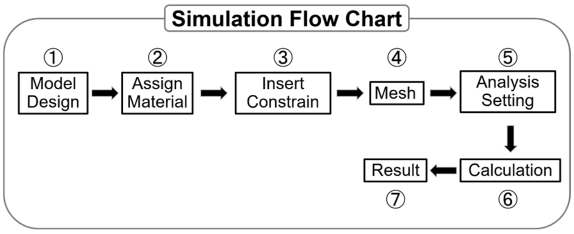

Figure 3: FEM simulation flow chart.

Figure 4 shows the FEM simulation results on each deformation. All deformations pressure was set up to 100 kPa. Bend deformation shows a bending angle of 10 degrees after pressurizing 15 seconds of constant pressure. The bulge deformation determined that the highest point of the bulge actuator could reach the soft palate, which in our model, would be 38.5 mm from the normal condition. The flap deformation indicated 39 degrees of flap angle symmetrically.

3 FABRICATION & ASSEMBLE GUIDELINES

There are seven types of fabrication in the soft robotics field: molding, reinforcements, additive

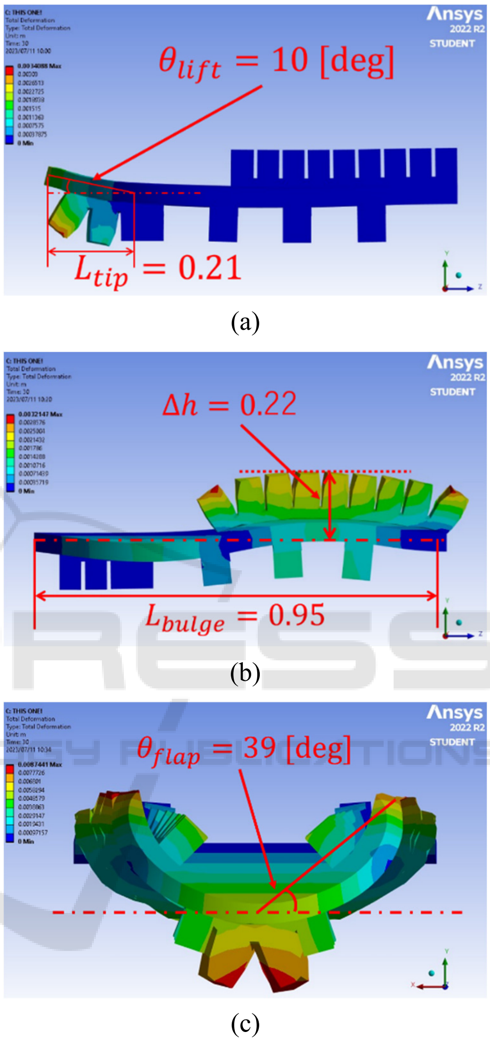

Figure 4: FEM simulation result on each deformation. (a) bend deformation. (b) bulge deformation. (c) flap deformation.

manufacturing, thin-film manufacturing, shape deposition manufacturing, bonding, and architectural considerations (Schmitt et al., 2018). In our case, to produce a soft actuator (PneuNets actuator) which is the internal structure is crucial, we are applying the molding (molding and casting) method. Molding and casting methods are easy to utilize for the soft robotic field, and the cost is reasonable.

Our soft robotic tongue required preliminary preparation and multiple processes before it

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assembles into one system. We have tried many fabrications, and copying the actual size of the human tongue is challenging to produce due to the small scale of the air inlet, and some chamber layers were ripped even before demold or separated from the mold. Accordingly, we determined to fabricate all parts into five times bigger than the original size of a human tongue. Based on the average of Oliver's measuring results (Oliver & Evans, 1986), the human tongue has a dimension: length of 34.95 mm, breadth of 43.70 mm, and thickness of 10.60 mm. The five times fabricated size will have a dimension: length of 174.75 mm, width of 218.50 mm, and thickness of 53.00 mm.

3.1 Mold

Mold is needed to copy the model of the soft robotic tongue. Mold data was made using SolidWorks and preliminary printed using a 3D printer. The base plate and each soft actuator mold are shown in Figure 5. Each mold was sprayed with a release agent before starting casting.

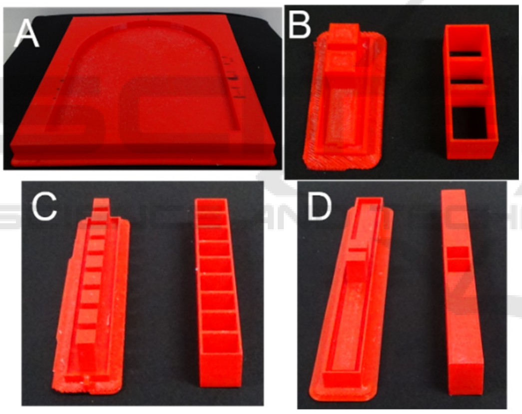


Figure 5: Base plate (A), bend actuator (B), bulge actuator (C), and flap actuator (D) mold printed using a 3D printer.

3.2 Casting

For casting, we use Ecoflex 00-30 silicone rubber liquid with a durometer of 30A produced by Smooth-On. The silicone liquid consists of Part A and Part B, which must be mixed before use. Afterwards, the liquid mixture is injected into the printed mold and cured for 2-3 hours. In addition, a different color pigment was added to the mixture to distinguish each soft actuator in the final product. Figure 6 shows the casting process.

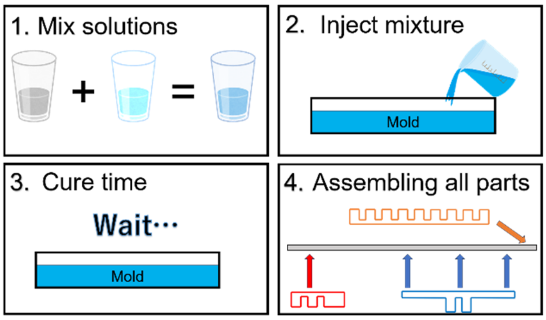
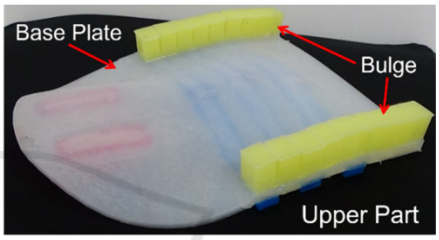


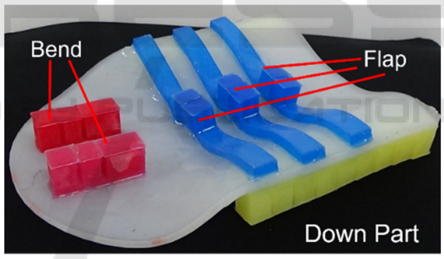
Figure 6: Scheme of the fabrication process.

3.3 Result

The fabrication result is shown in Figure 7. The yellow, red, and blue represent bulge, bend, and flap actuators.



(a)



(b)

Figure 7: Final design of the fabricated soft robotic tongue. (a) upper part. (b) down part.

4 EXPERIMENTAL RESULTS

This section will discuss the experimental equipment and method to measure and calculate parameters. In the experiment, we focus on the measurement to find the angles (bend and flap) and bulge parameters.

4.1 System Configuration

The equipment we used for the experiment is listed as follows: one PC, one Arduino, one air compressor, and three pressure control valves. Figure 8 depicts the system configuration for the experiment. Electro-pneumatic regulators are used to control the pressure and act as a continuous process. Each electro-pneumatic regulator receives the target pressure from the Arduino and controls the pressure being pressurized to the actuators. When the target pressure is issued, we achieve the steady state of the all-deformation's soft robotic tongue, which will be discussed in session 4.2.

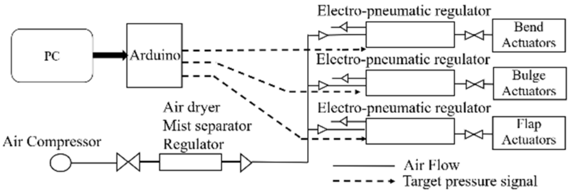
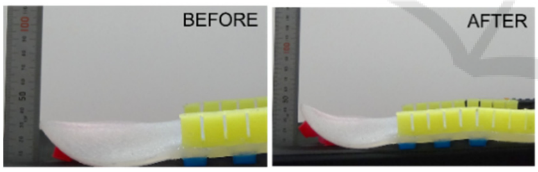


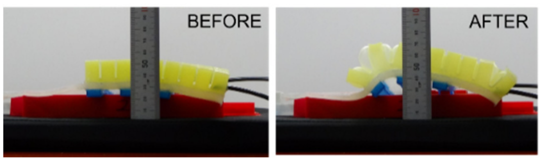
Figure 8: System configuration for experimental verification.

4.2 Method and Results

We configured the air pressure with a 12 kPa flow every second. Figure 9 shows the experimental results of the soft robotic tongue in a steady state. For bend movement, it successfully bent when the air was pressurized. Bulge movement shows it bulged vertically and shrank horizontally. While the flap movement was flapped closed to a letter U. The time scale for bend, bulge, and flap deformation to reach a steady state are 0.7 s, 0.8 s, and 15 s, respectively. The numerical value of experimental and FEM simulation data represents in Table 3.



(a)



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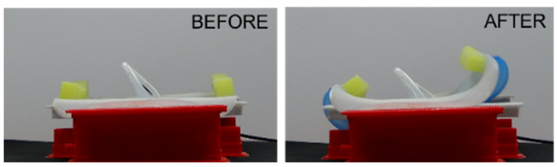


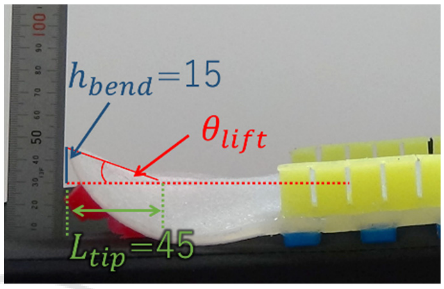
(c)

Figure 9: Experimental result of each deformation with comparison before and after pressurized. (a) bend deformation. (b) bulge deformation. (c) flap deformation.

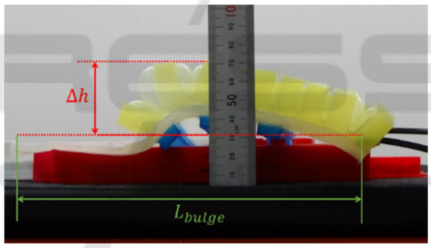
Table 3: Comparison of experimental and FEM simulation data.

Deformation	Parameter	FEM Data	Experimental Data
Bend	θ_{lift} [deg]	10	18
	L_{tip} [mm]	37	45
Bulge	Δh [mm]	38.5	39
	L_{bulge} [mm]	166	164
Flap	θ_{flap} [deg]	39	35

Figure 10 shows the notation parameter and its presentation using a simplified triangle diagram. The calculation of θ_{lift} and θ_{flap} was derived using $\tan^{-1}$. While Δh can be simply measured using a ruler.



(a)



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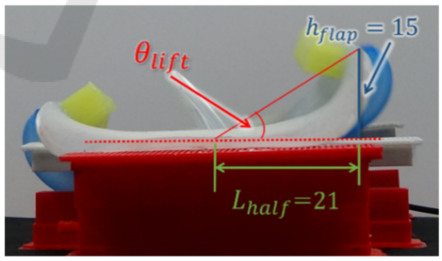

(c)

Figure 10: Notation parameter during air was pressurized. (a) bend deformation parameters, (b) bulge deformation parameters notation. (c) flap deformation with a presentation of a triangle diagram.

5 DISCUSSIONS

To evaluate the data we obtained from the experiment, we have to compare the data with the simulated FEM data. Based on the summarized data in Table 3, some experimental data values differed from the simulated FEM data.

The bend deformation shows a difference of 8 degrees and 8 mm on L_{tip}. For bulge deformation, it has a slight difference, 0.5 mm in Δh and 2 mm in L_{bulge}. Regarding flap deformation, the flap angle shows a difference error of 4 degrees. In addition, the result of flap deformation was not equal symmetrically when air was pressurized. The left part of the robot was lifted circularly stronger than the right part, resulting in the entire system tilted to the right. It is assumed that there was a human error during fabricating of the flap actuator; for instance, an error designed of the flap actuator's inner chamber wall (width of the wall) affected the flap actuator inflating strongly in the radial direction. To solve this, we plan to redesign and recheck if the design is identical to the model we used in the FEM simulation.

However, our goal is to use the soft robotic tongue to support visualizing the tongue motion of English pronunciation. Even if it has differences in numerical data, the practical usage is valid overall as long as the soft robotic tongue can mimic the movements visually.

6 CONCLUSION & FUTURE WORKS

We have suggested a novel soft robotic tongue that mimics English pronunciation movements. We make it to aim the improvement at learning support for English pronunciation. This paper discusses the fabrication process and evaluates the experiment, including the parameter of tongue movements of basic English pronunciations. Previously, we conducted a FEM simulation to confirm the deformation patterns of each basic tongue movement. We tried to fabricate the robot and demonstrate the motion based on the simulation results.

We utilized an elastic and flexible material, Ecoflex 00-30 elastomer. The fabrication process starts with making a mold of each soft actuator. After the fabrication finished, an experiment to validate the motion was directed. It shows that the movements in the simulation or the actual fabricated model have slight differences. The simulated model and experimental verification contribute to a study of the soft robotic and soft robotic tongue that mimics English pronunciation movements.

In the future, it would be better to measure each parameter using further precise tools such as flex sensors as feedback to obtain the experimental data more accurately. Some papers applied flex sensors to measure the bend or curvature angle in their work (Roy et al., 2015; Coral et al., 2015), and it gives us an idea to apply flex sensors to our soft robotic tongue in the future. Dynamics states analysis will be conducted in the future for parameter control of each deformation. Moreover, we will try to fabricate a tongue cover to cover up the entire system so it does not bother the appearance for practical usage.

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